ARMY RESEARCH LABORATORY

Experimental Firing Fixture for Evaluation and Calibration of Angular Rate Sensors During Actual Gun Firings

Timothy L. Brosseau
T. Gordon Brown

ARL-TR-2767 SEPTEMBER 2002

NOTICES

Disclaimers

Army Research Laboratory
Aberdeen Proving Ground, MD 21005-5066

ARL-TR-2767 September 2002

Experimental Firing Fixture for Evaluation and Calibration of Angular Rate Sensors During Actual Gun Firings

Timothy L. Brosseau
T. Gordon Brown
Weapons and Materials Research Directorate

Contents

EXPERIMENTAL FIRING FIXTURE FOR EVALUATION AND CALIBRATION OF ANGULAR RATE SENSORS DURING ACTUAL GUN FIRINGS

1. Introduction

Presently, there is a program to try to improve the accuracy of the 2.75-inch rocket by firing small side thrusters at the front of the rocket to make course corrections during flight. In order to know when to fire these side thrusters, it is necessary to continuously measure the angular velocity of the rocket in the yaw and the pitch directions with the use of angular rate sensors. Because of the small size and the low cost of the 2.75-inch rocket, the rate sensors currently used in other types of military rockets tend to be too large and much too costly. However, in the commercial field, small and inexpensive rate sensors have been developed by Tokin America Inc., Murata Manufacturing Co. Ltd., and Analog Devices and are presently being used in camcorders and automotive applications. These commercial rate sensors have a range of at least 100 deg/sec and a bandwidth of at least 50 Hz. Since the anticipated motion of the rocket during launch is about 40 deg/sec at a frequency of about 18 Hz, the commercial rate sensors should be more than adequate to perform the required measurements, as long as they are not adversely affected by the 80-g acceleration of the rocket during launch.

Therefore, before the rate sensors were mounted into the 2.75-inch rocket, it was necessary to evaluate and calibrate them during actual dynamic gun firing conditions similar to an 80-g rocket firing. To accomplish this, the Advanced Munitions Concept Branch, Weapons and Materials Research Directorate of the U.S. Army Research Laboratory (ARL) developed an experimental firing fixture that uses an M16A2 rifle firing M855 ball ammunition to provide an impulse to a hinged aluminum plate, 1.9 cm thick, onto which the rate sensors are attached. The M16A2 rifle and the M855 ball ammunition were chosen because they are readily available and are inexpensive.

2. Approach

The approach taken in conducting the evaluation and calibration of the angular rate sensors was to attach the rate sensors to the hinged aluminum plate along with a mirror. A small laser was used to emit a light beam onto the mirror that reflected it back to a position detector manufactured by United Technology Detector. The output from the position detector gave a precise unfiltered measurement of the angular position of the hinged aluminum plate, which could be compared to the integrals of the rate sensors output. This position detector is considered the reference/truth measurement.

An expensive Systron Donner quartz rate sensor (QRS-11-0010-101) mounted in a "MotionPak" package was also attached to the hinged aluminum plate. The "MotionPak" comes with an extensive and precise calibration for each individual sensor, which could be used to verify the calibration of the position detector and as a standard for the other inexpensive rate sensors that have calibration factors generally applicable to all sensors of that type.

During initial firings in the development of the experimental fixture, it was determined that the M16A2 rifle had to be isolated from the hinged aluminum plate because all the rate sensors erroneously responded to the stress waves incited in the hinged aluminum plate when the rifle was fired. The M16A2 rifle was isolated from the hinged aluminum plate by an energy-absorbing rubber material, referred to as "isodamp," which remained from previous firing experiments.

3. Experimental Firing Fixture

The experimental firing fixture is shown in Figure 1. The M16A2 rifle is free to recoil 1.27 cm to the rear when the round is fired. This rearward motion is transmitted to the hinged aluminum plate by means of a 1.27-cm diameter aluminum rod that is 64.77 cm long. Three 1.27-cm thick "isodamp" rubber pads, 2.54 cm square, are mounted between the end of the aluminum rod and the hinged aluminum plate. The length of the radius arm through which the hinged aluminum plate pivots is 73.66 cm. The hinged aluminum plate is stopped at the end of its travel by striking into the edge of an "isodamp" rubber pad, 12.07 cm long, 8.89 cm wide, and 1.27 cm thick. The aluminum rod, the "isodamp" rubber pads, and the hinged aluminum plate are shown in Figure 2. The Tokin rate sensor (CG-16D0), the Murata rate sensor (ENC-3JA), the Analog Devices rate sensor (ADXRS150), and the Systron Donner quartz rate sensor (QRS-11-0010-101) mounted in the "MotionPak" package are shown attached to the hinged aluminum plate along with the mirror (see Figure 3).

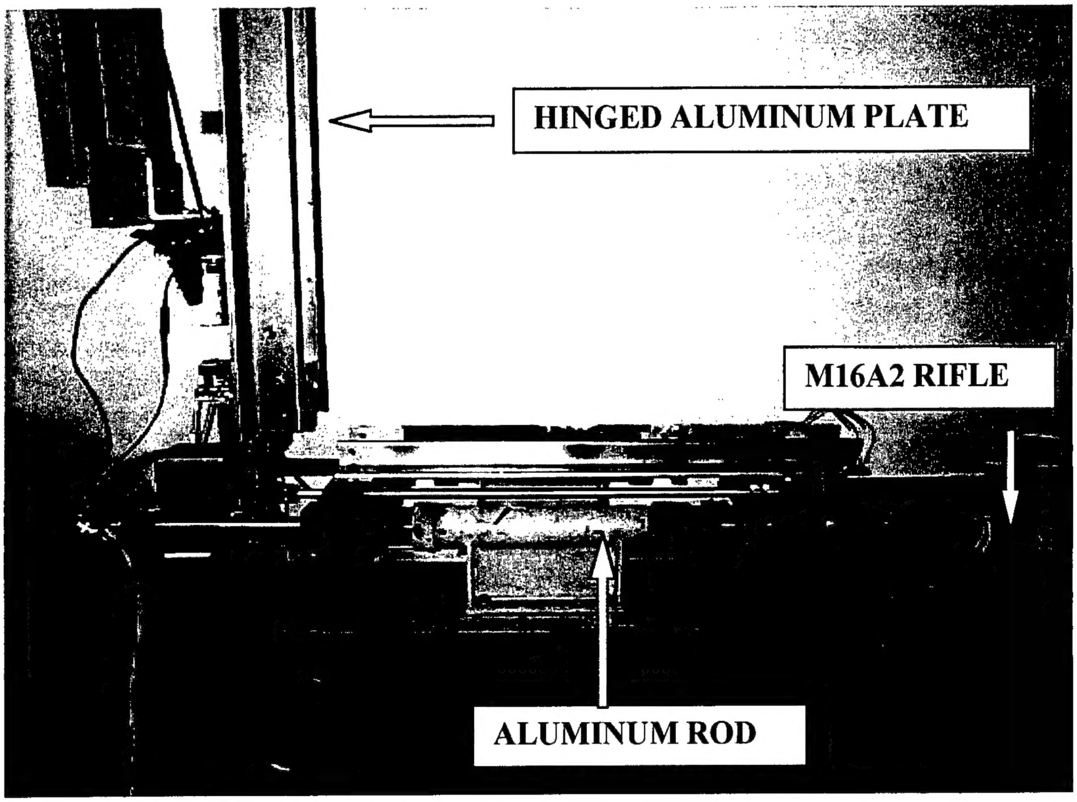

Figure 1. Experimental firing fixture.

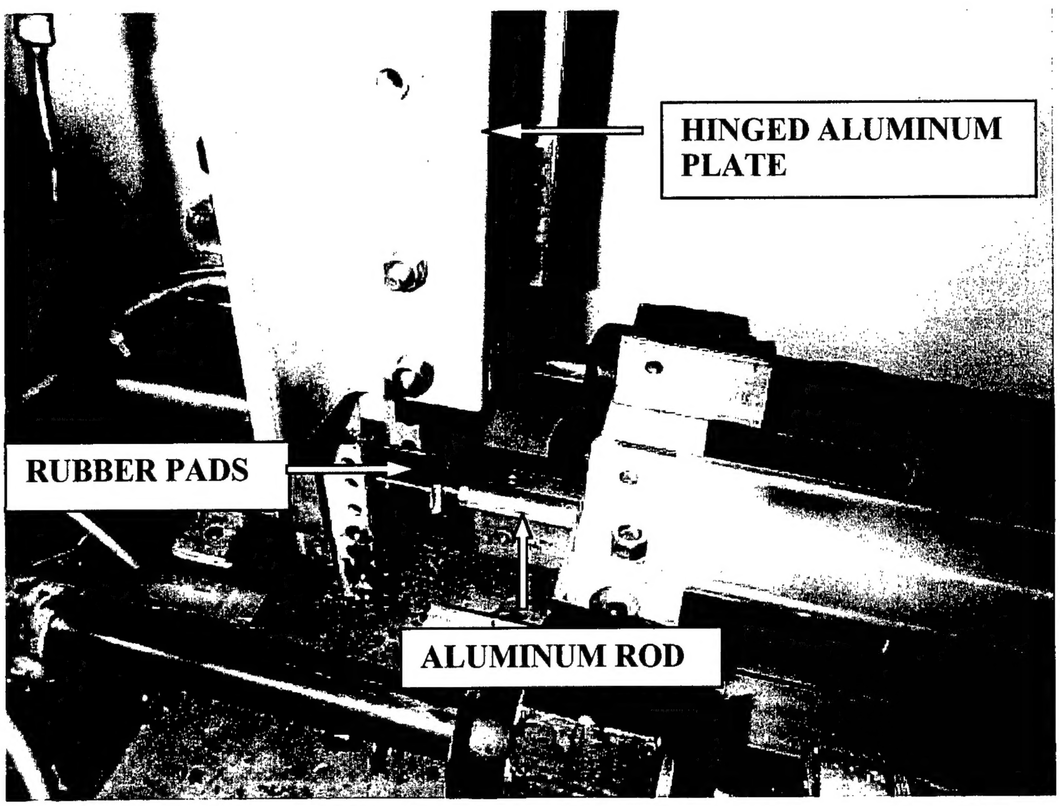

Figure 2. Aluminum rod, "isodamp" rubber pads, and hinged aluminum plate.

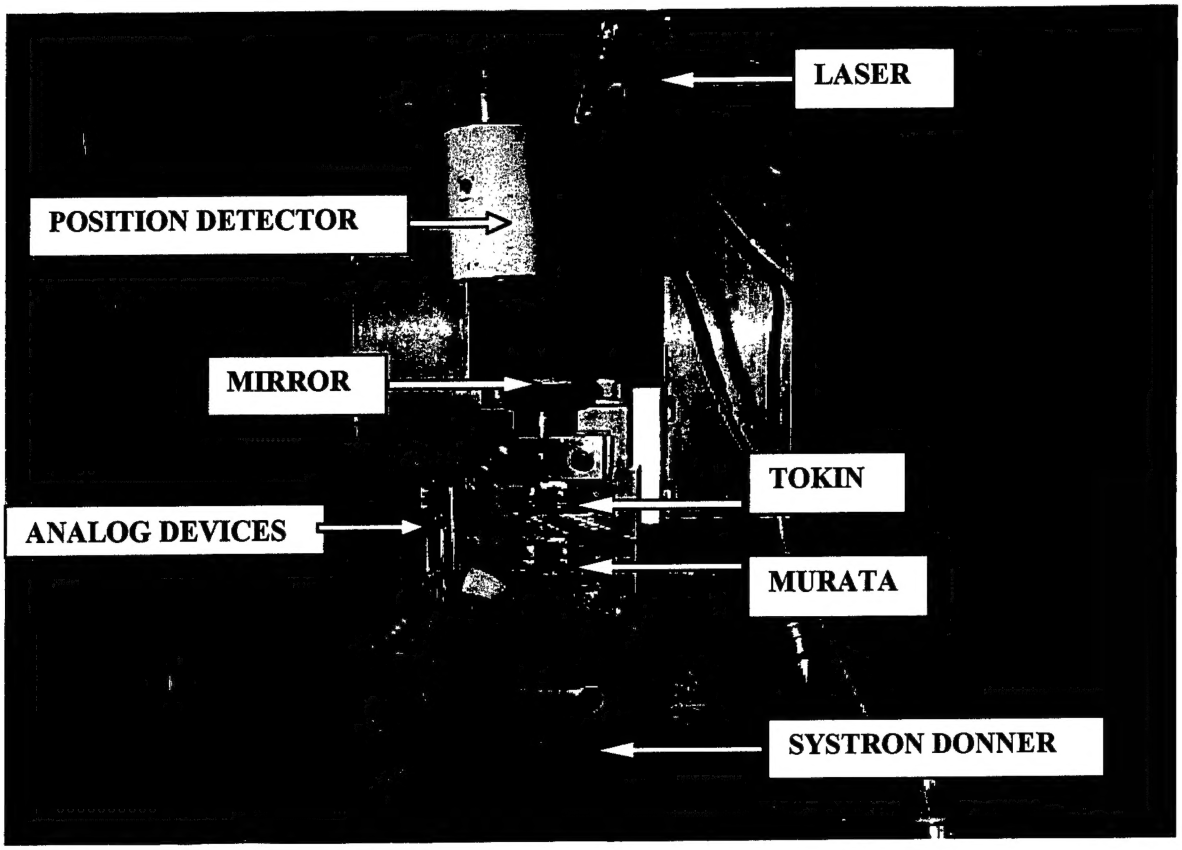

Figure 3. Angular rate sensors and mirror attached to hinged aluminum plate.

4. Non-Firing Experiments

Non-firing experiments were performed at an indoor range of ARL on Aberdeen Proving Ground (APG), Maryland. We performed the non-firing experiments by manually pushing the M16A2 to the rear. The maximum output from the Tokin, the Murata, and the Analog Devices rate sensors were then set equal to the maximum output from the Systron Donner rate sensor to obtain a calibration factor for each of the rate sensors. The calibration factor for the Tokin rate sensor was 1.26 mv/deg/sec. The calibration factor for the Murata rate sensor was 0.73 mv/deg/sec. The calibration factor for the Analog Devices rate sensor was 12.87 mv/deg/sec. The factory calibration factor for the Systron Donner rate sensor was 23.75 mv/deg/sec. With these calibration factors, the output signals from the rate sensors were integrated, recorded, and compared to the angular position obtained from the reference position detector. Before the experiments were performed, the position detector, mirror, and laser setup were precisely calibrated with a gunner's quadrant.

The recording and integration of the output signals were accomplished with a Hewlett-Packard "infinium" digital oscilloscope.

5. Results of Non-Firing Experiments

The results of the non-firing experiments are shown in Figures 4 through 7, which show the integrals of the output signals from the Systron Donner, the Tokin, the Murata, and the Analog Devices rate sensors plotted together with the angular position obtained from the reference position detector. Zero time in Figures 4 through 7 corresponds to the time when the threshold amplitude (trigger level) set on the position detector signal was exceeded and triggered the digital oscilloscope. Once triggered, a window of data was recorded, including before and after the trigger threshold. Since the trigger is referenced as zero time, a negative time may appear, depending on the defined window of data prescribed.

Figure 4 shows good agreement between the angular position obtained from the integrated output signal of the Systron Donner rate sensor, with its factory calibration factor of 23.75 mv/deg/sec, and the angular position obtained from the reference position detector, except for a slight time delay.

Figure 5 shows good agreement between the angular position obtained from the integrated output signal of the Tokin rate sensor, with a calibration factor of 1.26 mv/deg/sec, and the angular position obtained from the reference position detector, except for a slight time delay.

Figure 6 shows good agreement between the angular position obtained from the integrated output signal of the Murata rate sensor, with a calibration factor of 0.73 mv/deg/sec, and the angular position obtained from the reference position detector, except for a slight time delay.

Figure 7 shows good agreement between the angular position obtained from the integrated output signal of the Analog Devices rate sensor, with a calibration factor of 12.87 mv/deg/sec, and the angular position obtained from the reference position detector, except for a slight time delay.

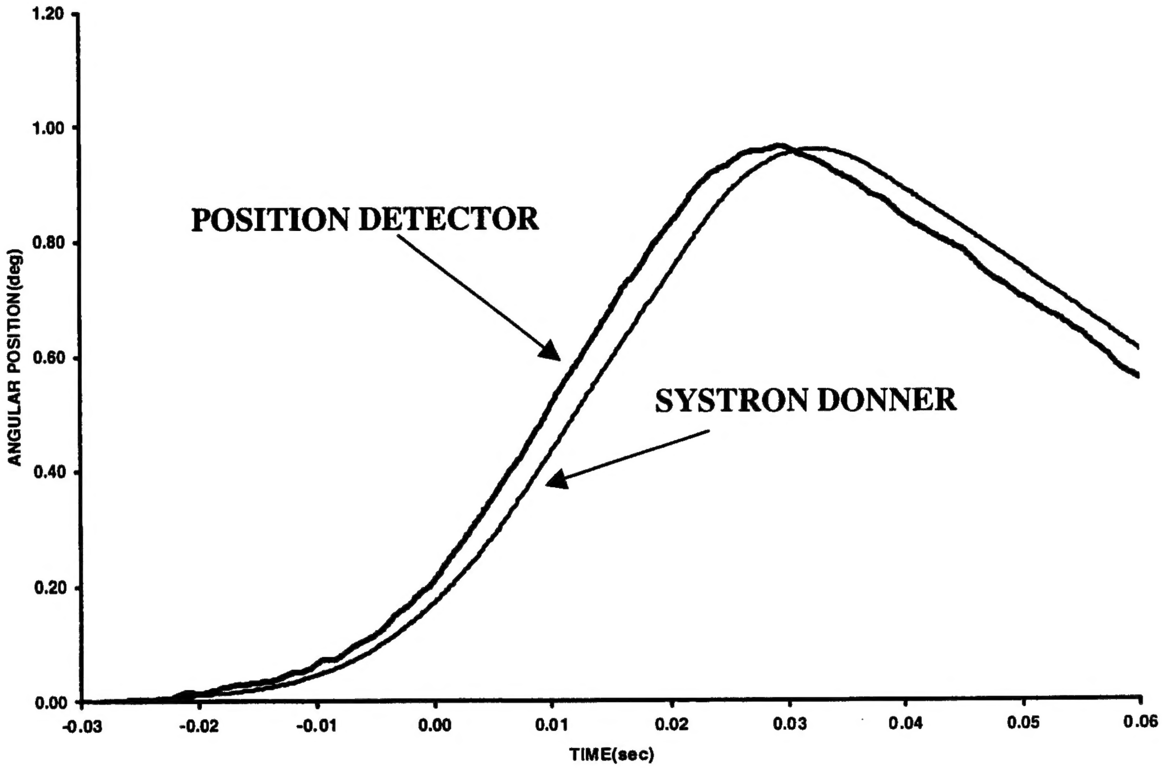

Figure 4. Integral of angular rate versus time for systron donner angular rate sensor during non-firing experiments.

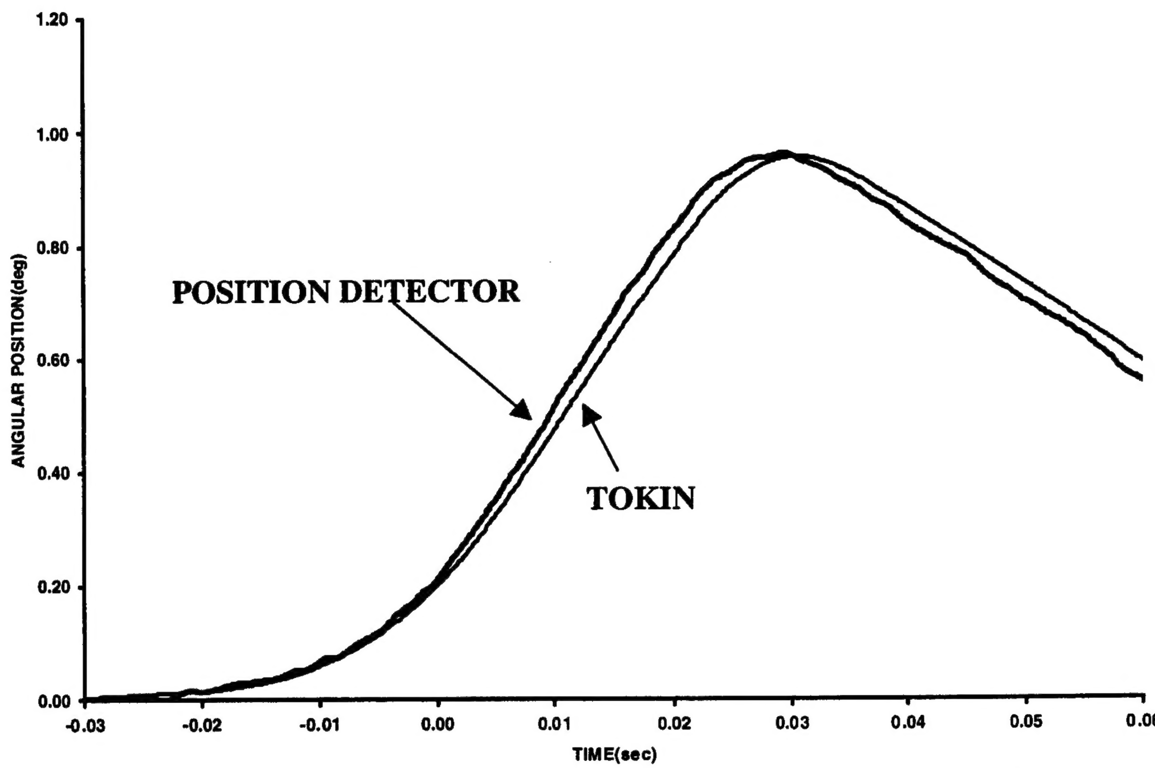

Figure 5. Integral of angular rate versus time for tokin angular rate sensor during non-firing experiments.

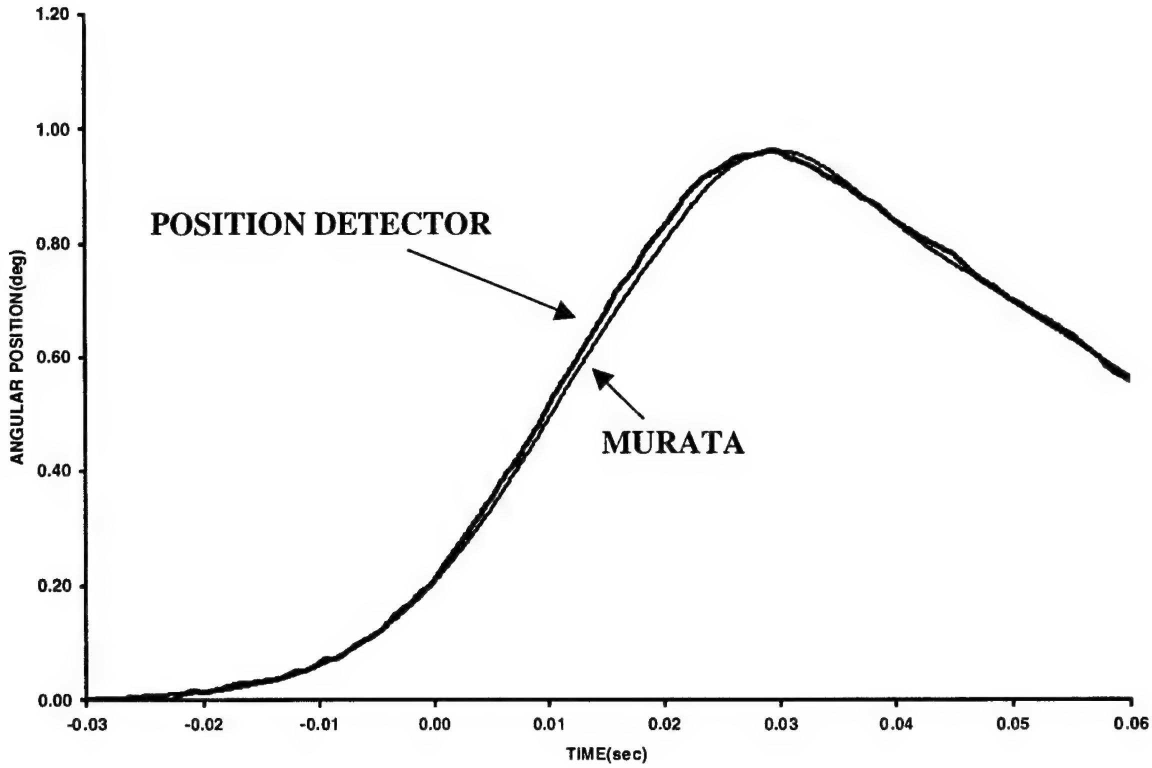

Figure 6. Integral of angular rate versus time for murata angular rate sensor during non-firing experiments.

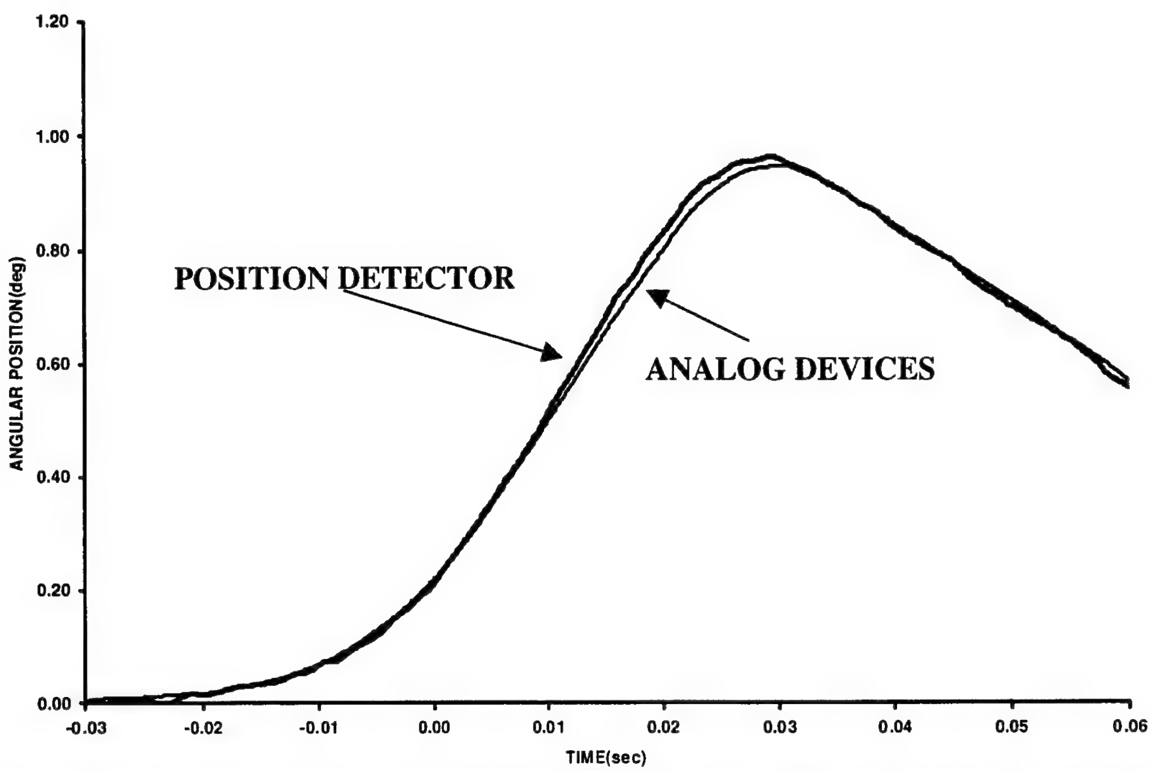

Figure 7. Integral of angular rate versus time for analog devices angular rate sensor during non-firing experiments.

6. Firing Experiments

After the non-firing experiments were completed, firing experiments were performed at an indoor facility of ARL at APG. The firing experiments were performed while M855 ball ammunition was fired from the M16A2 rifle. The output from the Systron Donner, the Tokin, the Murata, and the Analog Devices rate sensors was recorded with the same calibration factors as in the previous non-firing experiments. With these same calibration factors, the output signals from the rate sensors were then integrated, recorded, and compared to the angular position obtained from the reference position detector. The output signal from the reference position detector was also differentiated to obtain an unfiltered measurement of the angular rate, which could be compared to the output of the rate sensors in order to obtain a measurement of the time delays associated with the different filters used with the rate sensors.

The impulse from the firing of the ammunition round imparted an acceleration of about 100 g to the recoiling weapon and the hinged aluminum plate.

7. Results of Firing Experiments

The results of the firing experiments are shown in Figures 8 through 15; Figures 8 through 11 show the angular rates obtained from the Systron Donner, the Tokin, the Murata, and the Analog Devices rate sensors plotted together with the angular rate obtained from the differentiation of the signal from the reference position detector. Figures 12 through 15 show the integrals of the output signals from the rate sensors plotted together with the angular position obtained from the reference position detector.

Figure 8 shows that the band pass filter (~75 Hz), built into the Systron Donner rate sensor, removes the higher frequency (~400 Hz) component of the rate signal. However, the lower frequency (~17 Hz) component of the signal agrees well with the root mean square (rms) value of the unfiltered differentiated signal from the reference position detector, except for a time delay of about 3.0 ms. The maximum value of the rate, as measured by the Systron Donner rate sensor was about 80 deg/sec, which agrees well with the maximum rms. value measured from the unfiltered differentiated signal from the reference position detector.

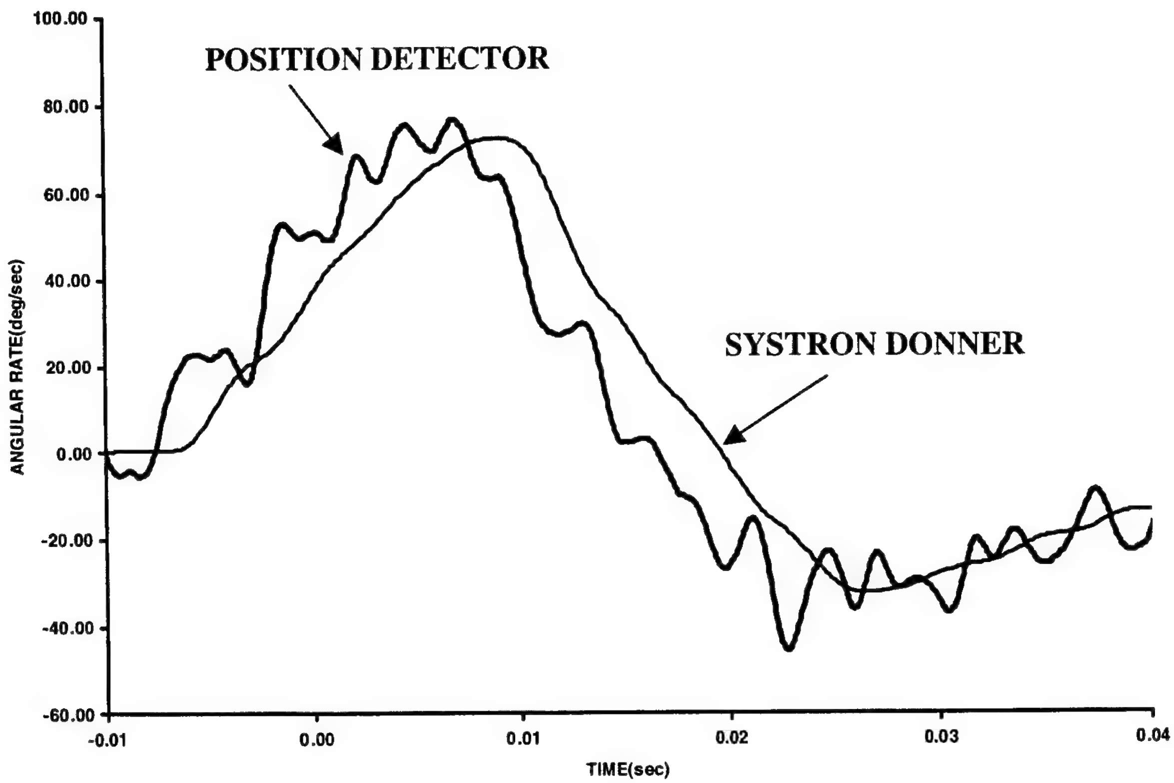

Figure 8. Angular rate versus time for systron donner angular rate sensor during firing experiments.

Figure 9 shows that the band pass filter (~100 Hz), built into the Tokin rate sensor, removes the higher frequency (~400 Hz) component of the rate signal. However, the lower frequency (~17 Hz) component of the signal agrees well with the rms value of the unfiltered differentiated signal from the reference position detector, except for a time delay of about 1.5 ms. The maximum value of the rate, as measured by the Tokin rate sensor, was about 80 deg/sec, which agrees well with the maximum rms value measured from the unfiltered differentiated signal from the reference position detector.

Figure 10 shows that the band pass filter (~100 Hz), built into the Murata rate sensor, removes the higher frequency (~400 Hz) component of the rate signal. However, the lower frequency (~17 Hz) component of the signal agrees well with the rms value of the unfiltered differentiated signal from the reference position detector, except for a time delay of about 1.5 ms. The maximum value of the rate, as measured by the Murata rate sensor, was about 80 deg/sec, which agrees well with the maximum rms value measured from the unfiltered differentiated signal from the reference position detector.

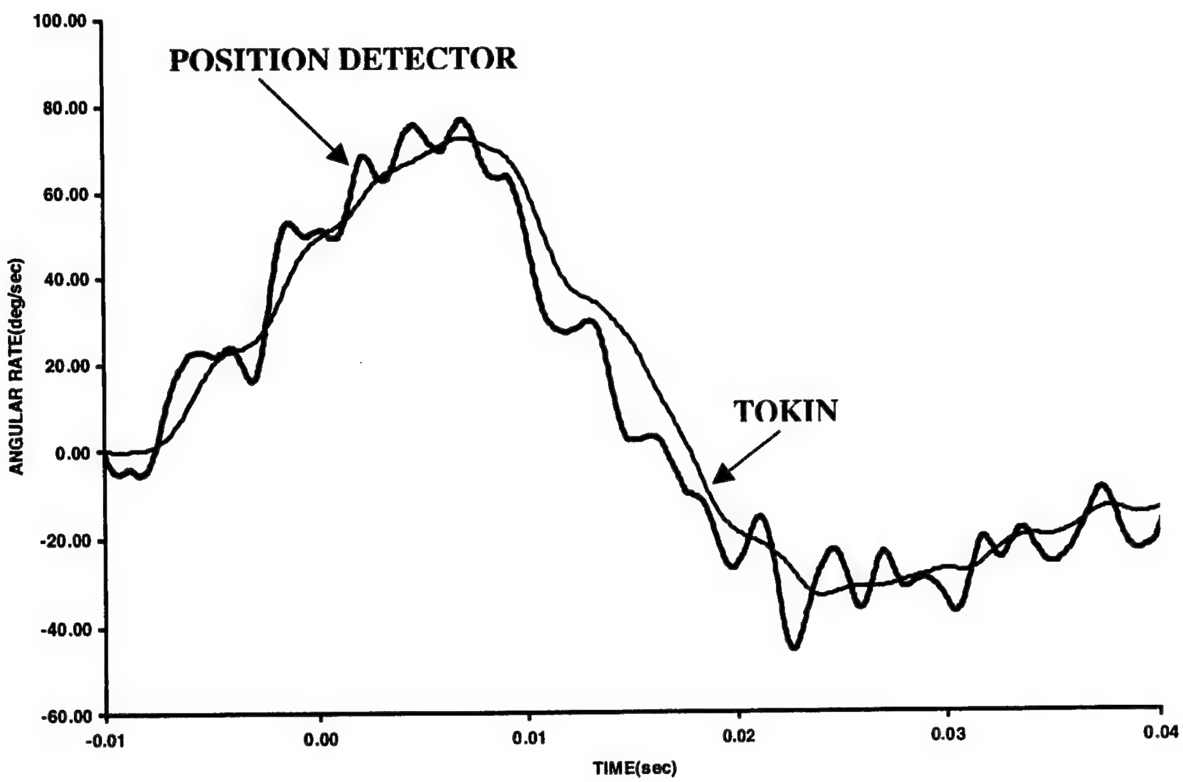

Figure 9. Angular rate versus time for tokin angular rate sensor during firing experiments.

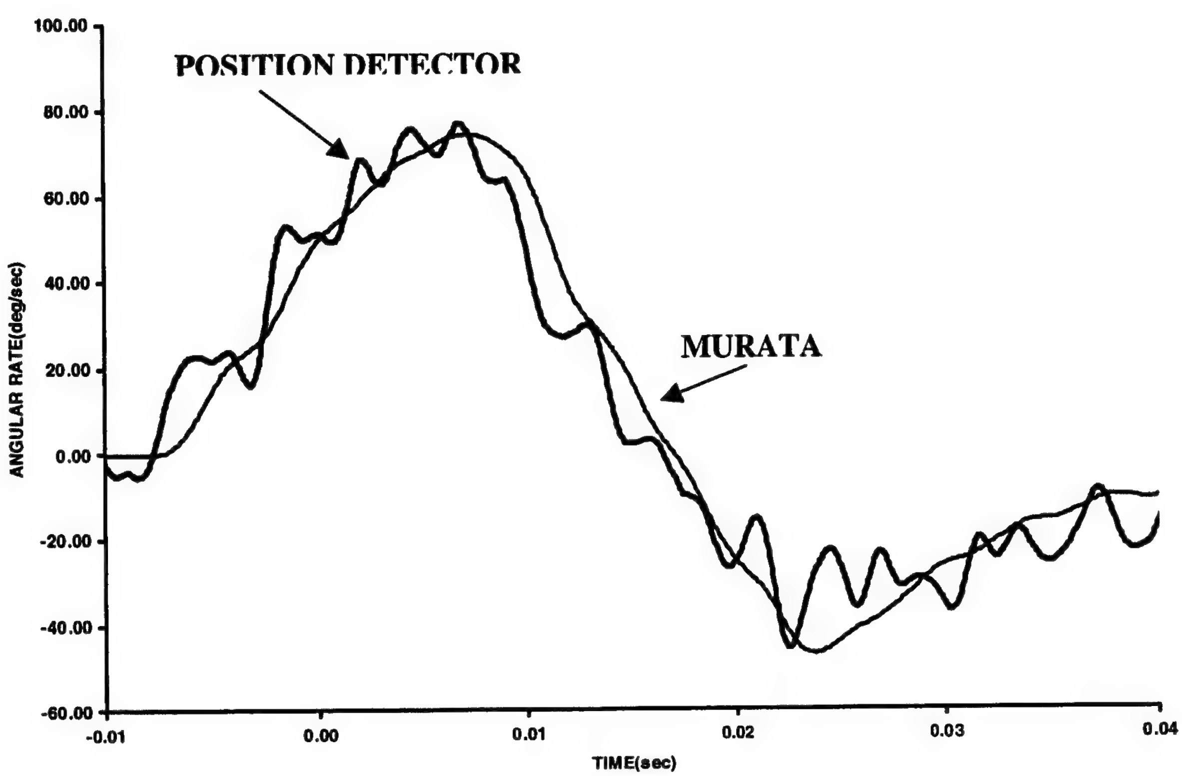

Figure 10. Angular rate versus time for murata angular rate sensor during firing experiments.

Figure 11 shows that the band pass filter (~200 Hz), built into the Analog Devices rate sensor, removes most of the higher frequency (~400 Hz) component of the rate signal. However, the lower frequency (~17 Hz) component of the signal agrees well with the rms value of the unfiltered differentiated signal from the reference position detector, except for a time delay of about 0.5 ms. The maximum value of the rate, as measured by the Analog Devices rate sensor, was about 80 deg/sec, which agrees well with the maximum rms value measured from the unfiltered differentiated signal from the reference position detector.

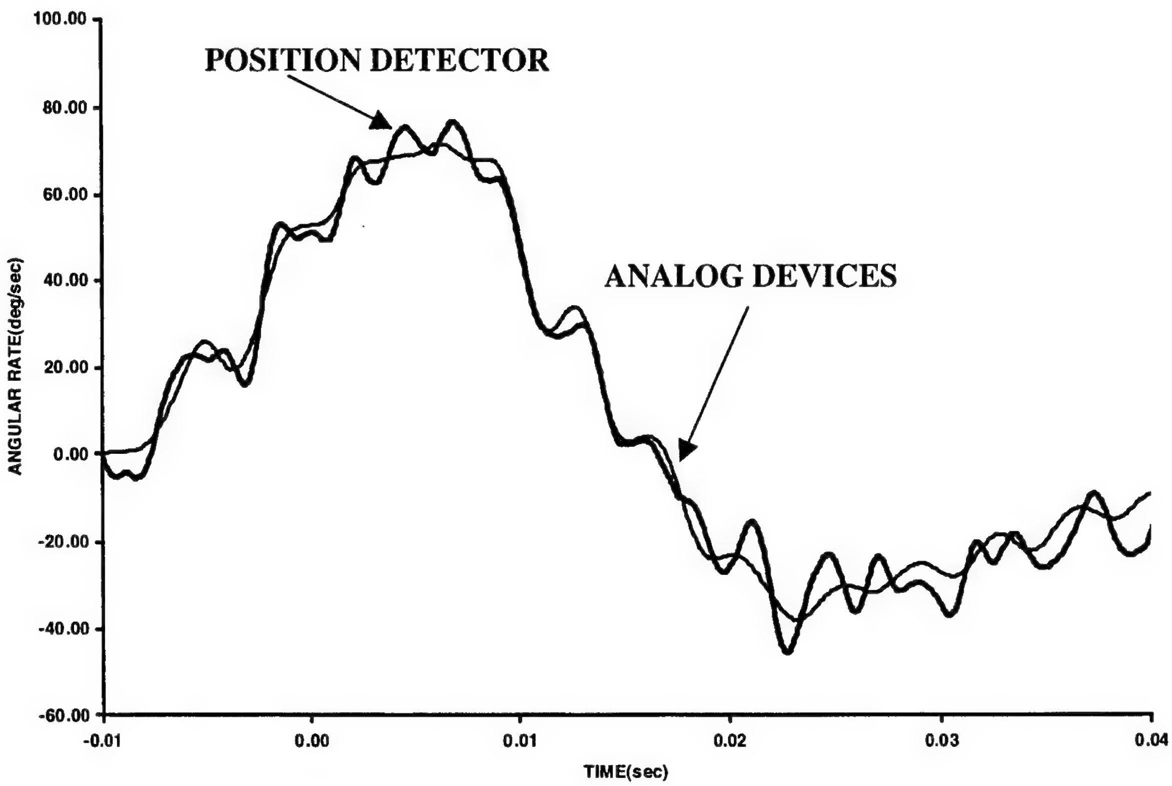

Figure 11. Angular rate versus time for analog devices angular rate sensor during firing experiments.

Figure 12 shows good agreement between the angular position obtained from the integrated output signal of the Systron Donner rate sensor and the angular position obtained from the reference position detector, except for the 3.0-ms time delay.

Figure 13 shows good agreement between the angular position obtained from the integrated output signal of the Tokin rate sensor and the angular position obtained from the reference position detector, except for the 1.5-ms time delay.

Figure 14 shows good agreement in the positive direction between the angular position obtained from the integrated output signal of the Murata rate sensor and the angular position obtained from the reference position detector, except for the 1.5-ms time delay. However, in the negative

direction, the Murata rate sensor appears to have a problem since the output signal returns downward from the maximum output much too quickly.

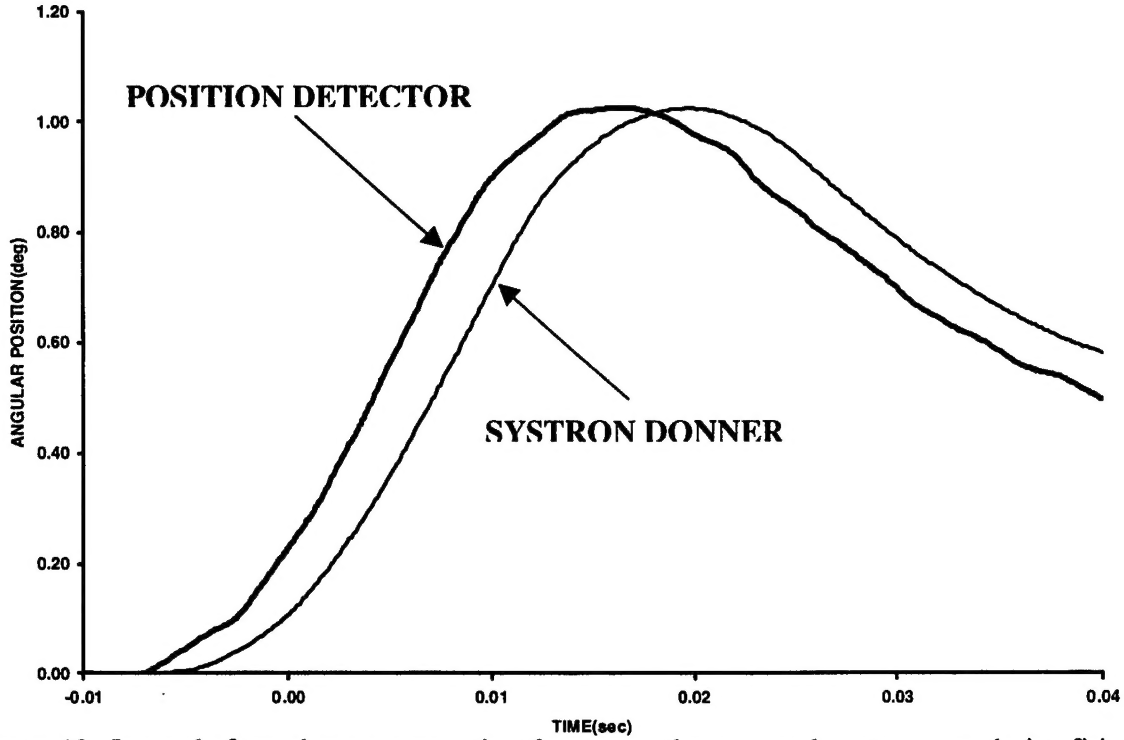

Figure 12. Integral of angular rate versus time for systron donner angular rate sensor during firing experiments.

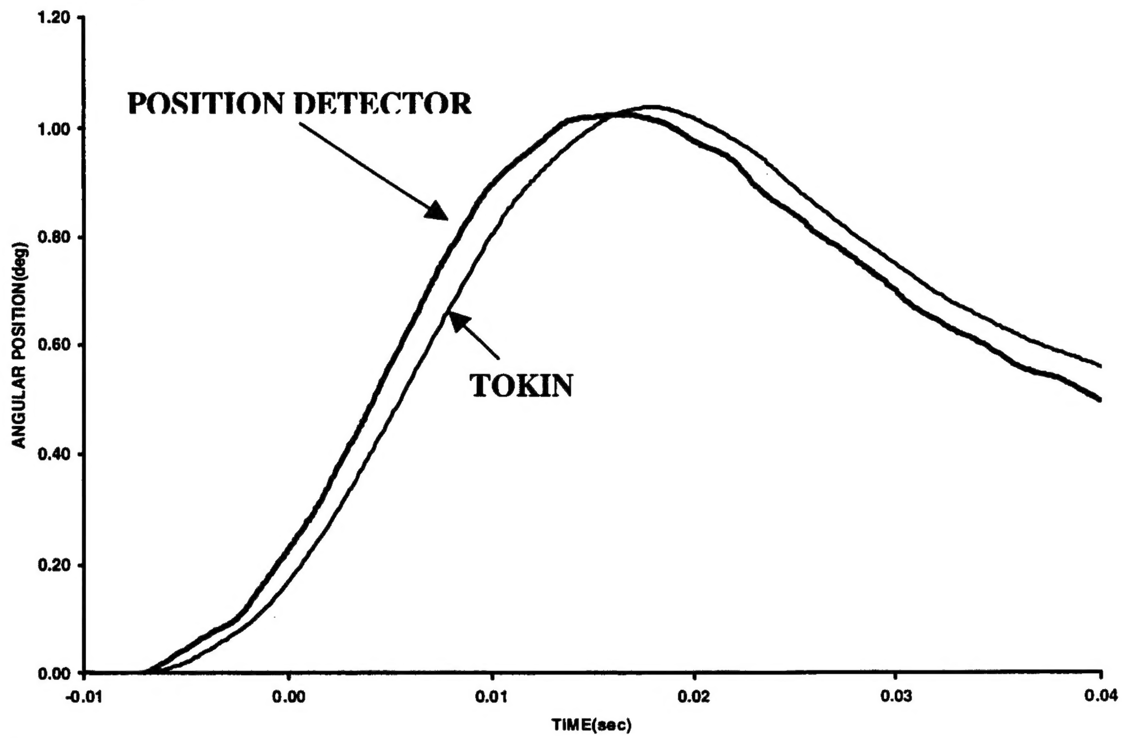

Figure 13. Integral of angular rate versus time for tokin angular rate sensor during firing experiments.

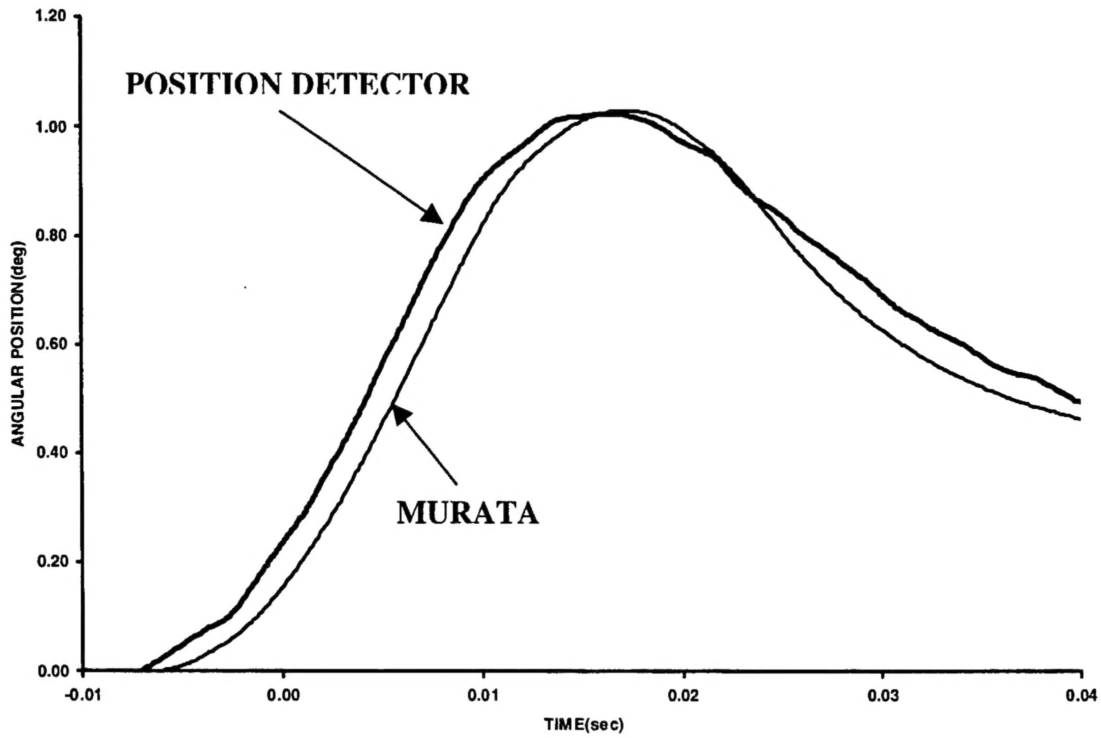

Figure 14. Integral of angular rate versus time for murata angular rate sensor during firing experiments.

Figure 15 shows good agreement between the angular position obtained from the integrated output signal of the Analog Devices rate sensor and the angular position obtained from the reference position detector, except for the 0.5-ms time delay.

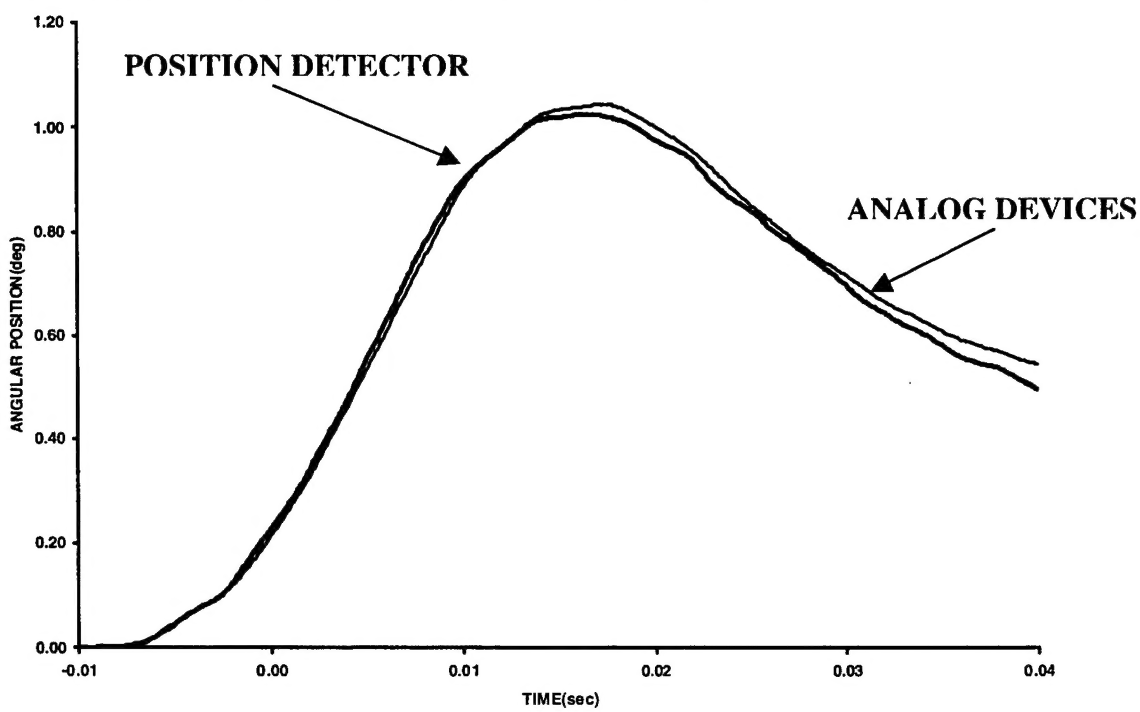

Figure 15. Integral of angular rate versus time for analog devices angular rate sensor during firing experiments.

8. Conclusions

The experimental firing fixture that used an M16A2 rifle firing M855 ball ammunition to provide an impulse to a hinged aluminum plate onto which rate sensors were attached performed well and provided a fast, inexpensive, and accurate means of evaluating and calibrating rate sensors during actual dynamic gun firing conditions.

During initial firings in the development of the experimental fixture, it was determined that the M16A2 rifle had to be isolated from the hinged aluminum plate by means of "isodamp" rubber pads because all the rate sensors erroneously responded to the stress waves incited in the hinged aluminum plate when the rifle was fired. This would seem to indicate that if any of these rate sensors were to be used in a rocket to measure angular rates during thrusting of the rocket, they would also probably have to be isolated from the stress waves incited by the burning rocket.

The results show that the output of the Systron Donner rate sensor, with a factory calibration factor of 23.75 mv/deg/sec, could be integrated to obtain a correct measurement of angular position at a frequency of about 17 Hz. However, the band pass filter built into the Systron Donner rate sensor is about 75 Hz, causing this angular position to be delayed by about 3.0 ms.

The results show that the output of the Tokin rate sensor, with a calibration factor of 1.26 mv/deg/sec, could be integrated to obtain a correct measurement of angular position at a frequency of about 17 Hz. However, the band pass filter built into the Tokin rate sensor is about 100 Hz, causing this angular position to be delayed by about 1.5 ms.

The results show that the output of the Murata rate sensor, with a calibration factor of 0.73 mv/deg/sec, could be integrated to obtain a correct measurement of angular position in the positive direction but not in the negative direction at a frequency of about 17 Hz. However, the band pass filter built into the Murata rate sensor is about 100 Hz, causing this angular position to be delayed by about 1.5 ms.

The results show that the output of the Analog Devices rate sensor, with a calibration factor of 12.87 mv/deg/sec, could be integrated to obtain a correct measurement of angular position at a frequency of about 17 Hz. However, the band pass filter built into the Analog Devices rate sensor is about 200 Hz, causing this angular position to be delayed by about 0.5 ms.

Results therefore indicate that the Tokin or Analog Devices angular rate sensors could replace a Systron Donner rate sensor in the measurement of angular rate in dynamic conditions. This is predicated on similar environmental considerations and similar signal conditioning. This appears to be an attractive alternative when one considers a potential 90% to 95% cost savings.

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	September 2002	Final

4. TITLE AND SUBTITLE

Experimental Firing Fixture for Evaluation and Calibration of Angular Rate Sensors During Actual Gun Firings

5. FUNDING NUMBERS

PR: 1L161102AH43

6. AUTHOR(S)

Brosseau, T.L.; Brown, T.G. (both of ARL)

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Army Research Laboratory
Weapons & Materials Research Directorate
Aberdeen Proving Ground, MD 21005-5066

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U.S. Army Research Laboratory
Weapons & Materials Research Directorate
Aberdeen Proving Ground, MD 21005-5066

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

ARL-TR-2767

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Presently, there is a program to try to improve the accuracy of the 2.75-inch rocket by firing small side thrusters at the front of the rocket to make course corrections during flight. In order to know when to fire these side thrusters, it is necessary to continuously measure the angular velocity of the rocket in the yaw and the pitch directions with the use of angular rate sensors. Because of the small size and the low cost of the 2.75-inch rocket, the rate sensors currently used in other types of military rockets tend to be too large and much too costly. However, in the commercial field, small and inexpensive rate sensors have been developed by Tokin America Inc., Murata Manufacturing Co. Ltd., and Analog Devices and are presently being used in camcorders and automotive applications. These commercial rate sensors have a range of at least 100 deg/sec and a bandwidth of at least 50 Hz. Since the anticipated motion of the rocket during launch is about 40 deg/sec at a frequency of about 18 Hz, the commercial rate sensors should be more than adequate to perform the required measurements, as long as they are not adversely affected by the 80-g acceleration of the rocket during launch.

Therefore, before the rate sensors were mounted into the 2.75-inch rocket, it was necessary to evaluate and calibrate them during actual dynamic gun firing conditions similar to an 80-g rocket firing. To accomplish this, the Advanced Munitions Concept Branch, Weapons and Materials Research Directorate, of the U.S. Army Research Laboratory developed an experimental firing fixture that uses an M16A2 rifle firing M855 ball ammunition to provide an impulse to a hinged aluminum plate, 1.9 cm thick, to which the rate sensors are attached. The M16A2 rifle and the M855 ball ammunition were chosen because they are readily available and are inexpensive.

This report describes the experimental firing fixture and also presents results of non-firing and firing experiments made for a Tokin rate sensor (CG-16D0), a Murata rate sensor (ENC-3JA), an Analog Devices rate sensor (ADXRS150), and a Systron Donner quartz rate sensor (QRS-11-0010-101).

14. SUBJECT TERMS	15. NUMBER OF PAGES
angular rate sensors	20
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102